HOT DRY ROCK-A CLIMATE CHANGE ACTION OPPORTUNITY FOR INDUSTRY

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Abstract

Geothermal resources in the form of heat found in rock that is hot but is not in contact with sufficient mobile fluid to transport that heat to the surface are a large, as yet virtually unexploited, source of clean energy. The technology to extract useful amounts of energy from this ubiquitous hot dry rock (HDR) geothermal resource has been under development for more than twenty years. During the last two years, flow testing at the Fenton Hill HDR pilot facility in New Mexico has answered many of the questions about the viability of HDR heat mining. While the most important issue of thermal longevity of the artificial geothermal reservoir that is the heart of an HDR energy system was not fully resolved, the test results provided good reasons to be optimistic that such reservoirs can have long lifetimes. No decline was observed in the temperature of the fluid produced during the relatively short test period and tracer testing indicated that the reservoir may be thermally self sustaining. In addition, water consumption during the circulation test was reduced to very low levels, the production of significant excess energy over that required simply to operate the system was verified, and routine energy production with virtually no emissions to the environment, except waste heat, was demonstrated.

The HDR pilot facility was completely automated and routine operations were carried out with virtually no human intervention, indicating the potential for low operating overhead in future commercial HDR plants. The benign geochemistry of the circulating fluid as well as the repair record during operations provided positive evidence that maintenance of HDR facilities should not pose major problems with regard to either cost or downtime. Finally, short experiments with modified operating cycles and reservoir modeling studies conducted in conjunction with the testing showed that further improvements in the productivity of HDR systems should be achievable by the application of relatively straightforward engineering and operating procedures.

On the basis of these encouraging test results, the Department of Energy issued a solicitation of private industry interest in the construction and operation of an HDR facility to produce and market energy from HDR resources. The proposed project will be industry-led but will involve government financial participation to reduce the capital risk. Hard figures on capital construction costs associated with the development of practical HDR plants will be developed as the plant is designed and built. The revenues generated from energy sales will pay for the operating costs and, hopefully, produce a profit for the developer of the facility. The stage will then be set for the full commercialization of HDR technology to help generate the large amount of clean power that will be required both in developed and rapidly developing countries as the 21st century unfolds.

Background

Geothermal resources are widely recognized as clean sources of energy. Typical geothermal plants generate far lower quantities of carbon dioxide, sulfur dioxide and oxides of nitrogen per unit of energy produced than any fossil-based energy facilities including those powered by natural gas. Unfortunately, conventional geothermal resources of steam and hot water are limited in both absolute quantity and geographical distribution. These hydrothermal resources, however, constitute but a small fraction of the total geothermal resource base. An almost unlimited amount of geothermal energy lies stored in rock that is hot but is not in contact with a natural source of mobile fluid to transfer that heat to the surface for use by man. Development of this hot dry rock (HDR) resource presents an opportunity for the geothermal energy industry to make a major contribution to the mitigation of climate change while at the same time building a large and profitable energy business.

The technology to extract energy at useful rates from the vast and ubiquitous HDR resource has been under development for the past 22 years. The concept upon which all l HDR development work has been based originated in the early 1970's and was disclosed in a patent, now expired, issued to the Los Alamos National Laboratory in 1974 (Potter, et al). A small HDR reservoir was created at Fenton Hill, NM during 1974-1978 and operated intermittently during 1978-1980 to prove the scientific feasibility of extracting energy from HDR. During 1980-1986, a larger, deeper, and hotter HDR reservoir was developed at Fenton Hill. Between 1987 and 1991, a surface plant, designed to power-industry standards and capable of extended operation, was constructed and mated to the large HDR reservoir. Flow testing of this Phase II HDR system was conducted during 1991-1993. The results of that flow testing have demonstrated the potential for HDR to be a practical source of geothermal energy. These results, as well as related work in modeling the behavior of the Fenton Hill HDR reservoir, are described in some detail below.

Recent Flow Testing at Fenton Hill

The Long-Term Flow Testing Program

The goal of the long-term flow test (LTFT) program at Fenton Hill was to demonstrate that HDR reservoirs could be operated on a continuous basis to produce useful amounts of energy over an extended period of time. In the process of conducting this test, answers were sought to questions involving the expected thermal lifetime of HDR reservoirs, water consumption, operating and maintenance costs, and the geophysical, geochemical, and environmental effects of long-term operation of an HDR system.

As a result of intensive discussions with the HDR Program Industrial Advisory Group, the LTFT was designed to simulate as closely as possible the conditions under which a commercial HDR power plant might operate. The pressure under which water was pumped into the injection wellbore was adjusted to the highest level that could be maintained without leading to expansion of the reservoir volume, as indicated by the onset of microseismic events and a very high rate of water consumption. Experience had shown that, for the Fenton Hill reservoir, this pressure was just under 27.5 MPa (4,000 psi).

A pressure of 9.7 MPa (1400 psi) was typically maintained on the production wellhead during steady-state circulation in order to prop open, by means of this imposed backpressure, the fluid carrying joints in the relatively low pressure region of the reservoir immediately adjacent to the production wellbore. The system pressure was reduced to about 4.8 MPa (700 psi) through a control valve at the outlet of the production wellhead and this pressure was maintained until the water was returned to the injection pump for repressurization and reinjection into the reservoir. The plant was computer-controlled, with fluid circulation maintained continuously on a 24-hour-a-day basis under these constant operating conditions. For much of the test period, the facility was manned only during the daylight hours. On a number of occasions, usually as a result of power failures caused by local weather conditions, the plant went into an automatic shutdown mode. In every such instance, the computer control system performed flawlessly.

Important system parameters such as pressure, temperature, and flow rate were monitored continuously. Measurements of the geochemistry of the circulating fluid were made several times a week. Diagnostic procedures such as production-well temperature logging and tracer analyses were implemented every few weeks or at critical junctures in the test program.

Fluid circulation began at the Fenton Hill HDR plant on April 8, 1992 and continued with only minor interruptions for 112 days. Then, the first phase of testing was terminated when leaks developed in both diesel-powered, reciprocal injection pumps within a two-day period. A subsequent investigation showed that the leaks were due to hairline cracks in the cylinder blocks of the pumps. The fatigue cracks appear to have been initiated at points of stress concentration in the stainless steel alloy from which the blocks were cast. The stress concentrations in turn arose from phase separation of the alloy as the blocks were cooled after casting. Although the pump failures were not related to HDR technology, the ensuing lapse in testing while suitable replacement pumping capacity was being evaluated, procured, and installed, was a serious setback to the LTFT effort.

By mid-February 1993, a replacement pump was installed at Fenton Hill and a second continuous phase of flow testing was begun. The new pump was a leased centrifugal unit powered by electricity. Once the appropriate modifications to the electric power supply at the site had been implemented, it proved to be highly reliable. The second continuous test period ran for 55 days until mid-April 1993, when the available funding was exhausted. Typical operating parameters during the two steady-state test phases are summarized in Table 1.

TABLE 1
LTFT OPERATING DATA

	July 21-29 1992	April 12-15 1993
Injection		
Pressure, psi (mpa)	3958 (27.3)	3965 (27.3)
Flow, gpm (l/s)	107 (6.8)	103 (6,5)
Temperature, ^{o}F(^{o}C)	66 (19)	72 (22)
Production		
Pressure, psi (mpa)	1400 (9.7)	1400 (9.7)
Flow, gpm (l/s)	89.7 (5.7)	90.5 (5.7)
Temperature, ^{o}F(^{o}C)	361 (183)	363 (184)
Water Consumption		
Rate, gpm (l/s)	12.5(0.79)	7.3 (0.46)
% of Ingected Volume	11.7	7.0

Results of Recent Steady State Flow Testing

Substantial new information was generated during the LTFT in regard to a number of important aspects of HDR technology. The most significant findings are discussed individually below:

Thermal Stability: The data of Table 1 indicate that there was no decline in the temperature of the fluid produced at the surface over the course of the flow-test period. At several points during testing, the production temperature was measured at depth by conducting a wire-line log of the production well while circulation was maintained. Figure 1 compares the temperature profiles obtained from three such logs.

Figure 1

Figure 1. Temperature profiles obtained from logging runs during recent flow testing. The temperature remained constant at the deepest part of the wellbore but the thermal loss to the surrounding rock as the hot water traveled up the production wellbore was greater in September when the flow rate was lower.

In all cases, the temperature measured at 3.27 km (10,800 ft), the depth which marks the top of the reservoir, was essentially the same. The logs indicate that a significant amount of energy is lost to the surrounding rock as the water travels up the wellbore to the surface. This energy loss becomes progressively greater as the rate of flow declines. Thus, the log conducted in September 1992, during a period of sub-optimal pumping and lower flow, shows the same temperature at depth as the other two logs, but a much lower temperature at the surface.

Tracer evidence provided even more encouraging data with regard to reservoir thermal stability. The results of a series of tracer tests conducted during the period of recent flow testing are presented in Figure 2.

Figure 2

Figure 2. Results of tracer tests conducted during recent flow testing. The times to initial appearance of the tracer and to the point of maximum rate of tracer return became longer as shorter, ostensibly cooled, flow paths closed and longer, more circuitous flow paths through the reservoir rock developed.

Remarkably, the tracers took longer to appear at the production well as the testing proceeded. The time to the point of maximum tracer return also lengthened. In effect, the tracer material (and by implication the circulating water) was taking longer and longer to get through the hot rock reservoir, indicating that more of the fluid was traveling across the reservoir via longer flow pathways and the shortest, perhaps most rapidly cooled, flow paths were closing off. This is exactly the opposite of the typical behavior in which water, once having found a route through a medium, continually enlarges that pathway. The reason for this seemingly anomalous behavior has not been determined but it may be related to fluid viscosity increases in the cooled pathways. In any event, this tracer evidence strongly suggests that the reservoir is self-sustaining to at least some degree, since the flowing fluid is continually gaining access to new hot rock within the reservoir.

Water Consumption: The amount of water that is lost to the subsurface in operating an HDR facility is a major concern, especially in those regions such as the American west where water resources are scarce. Table 1 shows that water consumption averaged about 12% toward the end of the first continuous phase of the LTFT, but only 7% near the end of the second phase. The slow but steady decline in water consumption confirmed earlier static pressure testing results which indicated that water losses decline as the microcrack fabric of the rock at the periphery of the reservoir becomes saturated at any particular pressure level (Brown and Robinson 1990; Brown 1991).

Net Energy Production: Thermal energy was regularly produced during the LTFT at a rate of about 4 thermal MW. This is approximately 6.3 times the thermal energy content of the diesel fuel and electricity consumed in running the system during the first phase of the test. In other words, the heating value of the fuel used to operate the plant was increased by a factor of more than six by using it to pump geothermal energy to the surface rather than using it directly as a heat source.

Environmental Effects: Under normal operating conditions there were no emissions from the HDR pilot facility except waste heat. The dissolved gases in the circulating fluid remained at low and essentially constant levels throughout the test. The only gas present in significant amounts was carbon dioxide. At the concentration found in the geofluid, all the gases remained in solution at pressures in the range of 2 MPa (300 psi). Since the circulating system pressure was kept at 4.8 MPa (700 psi), the gases in the fluid remained in solution and were not released to the atmosphere.

One important gas often encountered in underground fluids is hydrogen sulfide. This extremely toxic compound is heavier than air and tends to settle in low spots if it is released. Although signs posted at the Fenton Hill HDR site warn of the potential danger from hydrogen sulfide and a number of automatic alarms would announce its presence at a level well below that at which it would present any danger, the concentration of hydrogen sulfide in the circulating fluid at Fenton Hill has always been extremely low (typically less than 1 ppm). Even in the event of an unexpected release to the atmosphere, the risk arising from this low level of hydrogen sulfide would be very small.

The dissolved solids found in the circulating fluid were generally those characteristic of normal slightly saline fluids, mostly sodium, magnesium , calcium, and chloride, but with small amount of other materials, such as silica and arsenic, which tend to be present in crystalline rock. At a total solids content of about 0.4%, the Fenton Hill fluid was nearly an order of magnitude less saline than the ocean which contains about 3% salt.

System Maintenance Issues: Except for the injection pump breakdown mentioned earlier in this article, no major maintenance problems were encountered during the flow test period. Based on the low and stable levels of dissolved gases and solids, the almost total absence of suspended solids, and the relatively neutral pH of the circulating water (always greater than 5), neither scaling or corrosion would be expected. A caliper log of the injection tubing was conducted in late 1993, several months after the flow test was terminated. In spite of the fact that the tubing had been installed nearly 10 years earlier, the walls showed no signs of deterioration or of excessive scale formation. In short, all the evidence at Fenton Hill indicates that facility maintenance should be relatively simple and inexpensive for HDR systems utilizing reservoirs created in hard, crystalline rock.

Results of Recent Cyclic Operations Testing

Observation of the pressure response on a number of occasions when circulation was halted by closing both well heads had indicated that most of the resistance to flow across the HDR reservoir was concentrated in the region of the reservoir near the production wellbore. Expressed another way, the majority of the pressure drop between the 27.3 MPa (3960 psi) injection pressure and the 9.7 MPa (1400 psi) production pressure applied during the LTFT occurred near the production wellbore. In concept, the production from the HDR reservoir therefore could be increased by periodically pressure dilating the joints near the production wellbore. This could be accomplished by closing the production well briefly, and thereby causing the pressure on the joints in the vicinity of production well to increase toward the pressure applied at the injection wellbore. If the joints were rapidly jacked open by this increased pressure, but they closed only slowly when the production well was reopened, it might be possible to obtain an overall increase in system productivity.

Near the end of the LTFT, a short experiment was conducted to test this idea (DuTeau 1993). It entailed brief shut-ins of the production wellbore once every 24 hours for three consecutive days. Figure 3 shows the production wellhead pressure and the production flow rate over the span of this short cyclic experiment.

Figure 3

Figure 3. Injection and production wellhead pressures and flow rates during the first cyclic test at the close of the LTFT.

As discussed above, the pressure peak at the production well during each short shut in appeared to jack open the reservoir joints in the region of the production wellbore The very high rate of production immediately following each shut-in period reflected both the release of pent-up fluid and the opened joints. The production rate declined rapidly at first as the surplus water was released, and then more slowly as the joints continued to close. After 24 hours, however, the production rate was still higher than it had been just prior to the shutdown. As shown in Figure 4, the total daily energy production increased by about 2% during each day of the test.

Figure 4

Figure 4. Total daily energy production just prior to- and during the first cyclic test at the close of the LTFT.

Had the test gone on longer, these daily rate increases would not have been maintained, but this short experiment clearly demonstrated that the long-term production decline evident in the early part of the data of Figure 4 could be easily reversed.

In a subsequent short cyclic test, the reservoir was alternately shut in for 16 hours and then operated for 8 hours (Brown 1993; Brown 1994). On May 6, 1993, a short time into the third production cycle of this experiment, a sudden and unexpected increase in flow was observed. Within less than a minute, the production flow rate increased nearly 48%. At this increased flow rate, the production temperature soon increased to over 190°C. Rather than continue the cyclic experiment, the system was brought into steady-state operation. Table 2 compares steady-state operating conditions a few days after the flow increase was observed to those of about a month earlier when phase II of the LTFT was still underway.

TABLE 2
Operating Data Before and After
Sudden Flow Increase of May 6, 1993

	May 13 1993	April 12-15 1993
Injection		
Pressure, psi (mpa)	3860 (26.6	3965 (27.3)
Flow, gpm (l/s)	130 (8.2)	103 (6,5)
Temperature, ^{o}F (^{o}C)	75 (24)	72 (22)
Production		
Pressure, psi (mpa)	1400 (9.7)	1400 (9.7)
Flow, gpm (l/s)	122 (7.7)	90.5 (5.7)
Temperature, ^{o}F (^{o}C)	374 (190)	363 (184)
Water Consumption		
Rate, gpm (l/s)	*	7.3 (0.46)
% of Ingected Volume	*	7.0

* Because of the Overpressurization during the 16-hour production shut-ins in early May, the apparent water consumption was less than zero (apparent net production of water) during the steady-state testing period following the sudden flow increase.

Note that although the production flow rate was much higher in May than in April, the injection pressure was lower. This was because the centrifugal injection pump could not maintain the maximum flow rate that was now possible in the altered reservoir. Unfortunately, funding limitations prevented testing of the altered reservoir beyond a few days. However, these dramatic results demonstrated that significant impedance reductions can be achieved by carefully designed pressure manipulations of HDR reservoirs.

The two cyclic experiments discussed above highlight the potential for maximizing the productivity of HDR reservoirs by the studied manipulation of operating schedules. Further experiments of this sort would no doubt bring additional improvements in reservoir performance and a better understanding of HDR systems. The funding for such important testing is not currently available, but as the feasibility of HDR for practical energy production becomes established, these experiments may form the basis for further work to improve the productivity of HDR systems.

Reservoir Modeling

GEOCRACK Application and Modification

Progress continued this year in the application of the GEOCRACK Finite Element Model to the simulation of flow in the Fenton Hill HDR reservoir. Recent results have shown good agreement between observed and modeled flow conditions at several different injection and production pressures. Consideration of tracer results obtained during recent long-term flow testing have prompted the incorporation of random flow blockages in the model flow matrix. These blockages distribute the flow through a broader region of the matrix and result in what appear to be more realistic flow paths.

As an example, Figure 5a shows a typical rock-block/flow-path mesh used in the GEOCRACK Model. In this construction, the injection point is at the lower left and the production point is at the lower right of the diagram (this figure shows only one quadrant of the modeled volume). The flow paths for a simulation based on this mesh, with one-third of the flow pathways randomly blocked, are shown in Figure 5b.

Figure 5a and Figure 5b

Figure 5. (a) A typical rock-block/flow-path mesh used in the GEOCRACK finite element HDR reservoir model. (b) Flow paths for a HDR flow simulation based on the GEOCRACK finite element mesh with one-third of the flow pathways randomly blocked.

The goal of these simulations is to construct a picture of the fluid flow which emulates the real conditions within the reservoir to a degree adequate to be of value in addressing important reservoir issues. These include engineering questions such as the optimum spacing and number of production and injection wells, as well as the effects of a wide variety of potential modes of reservoir operation on the productivity and longevity of HDR systems.

In tandem with the experimental results of recent flow testing, the GEOCRACK Model is providing some critical information about the HDR reservoir at Fenton Hill and, hopefully, HDR reservoirs in general. Initial observations include the following:

> Most of the reservoir impedance occurs near the production well. Reducing only this near-wellbore impedance may greatly increase productivity. Likewise, increasing the distance between the injection and production wells may give access to significantly more hot rock with only a marginally deleterious effect on overall system impedance.
>
> While a localized increase in permeability (reduction in impedance) in the vicinity of the production well may lead to an increase in production, this advantage may be partially lost since one effect may be to simply move this impedance barrier out to the boundaries of the increased-permeability zone.
>
> There appears to be a limit to the maximum injection pressure that can applied before the pressure relief value of the production well is exceeded and reservoir growth ensues. A single production well at each end of the reservoir may thus not provide the optimum pressure sink. A line of kick-off wellbores positioned across the width of the lowest-stress direction of the reservoir zone may be required to provide the most effective pressure relief and permit the use of the highest possible injection pressures without continual reservoir expansion.

Summary

After about 22 years of research and development, recent testing has clearly demonstrated the potential of HDR technology to produce clean energy on a continuous, highly-automated basis. The environmental advantages claimed for HDR technology have been verified in actual practice, concerns about water consumption have largely been laid to rest, and significant excess energy production over that required to conduct the HDR operation has been demonstrated.

Because the total circulation time (about 8 months) was short compared to the total time that an HDR reservoir would have to be operated in order to justify construction of commercial power plants. The thermal longeuity of such deep HDR reservoirs was not fully demonstrated in recent testing. The data obtained, however, were extremely promising. The temperature of the produced fluid showed no decline over the span of the test and tracer results indicated increasing access to hot rock with time. Concerns about short-circuit pathways developing and thereby causing a rapid decline in the temperature of the produced fluid proved to be unfounded and, in fact, the shorter flow paths appeared to carry proportionately less fluid as testing proceeded.

Routine operation of the HDR pilot facility, often with no manpower on site, demonstrated that HDR plants can be automated to the same degree as conventional hydrothermal facilities and that operational labor costs should be low. Operating experience indicated that both routine and special maintenance procedures should be relatively simple and inexpensive. The benign water chemistry as well as plant equipment and component inspections indicated neither corrosion nor scaling as serious problems.

Limited cyclic testing showed the potential for maintaining and even increasing the production from such HDR reservoirs by the application of a variety of operating scenarios. Modeling based on actual test results has been applied to predict that significantly larger reservoirs can be created and operated without significantly increasing the pressures required (and thus the pumping costs) to circulate fluid through the system. In short, recent testing, while limited in some respects, has given every indication that it will be possible to operate HDR plants in a commercially viable manner.

Future Plans

In light of the recent encouraging operational test results, the greatest challenge to the implementation of HDR technology now appears to be in the area of capital costs related to the development of the underground system. To date, all HDR reservoirs created throughout the world have been conceived and developed as research facilities. In all cases, more attention was paid to the collection of scientific data and to assuring the provision for a variety of experimental procedures than to a rigorous control of the costs of building the facility. As a result, no hard data on the capital requirements for the construction of a commercial-grade HDR plant are available.

A number of studies have been conducted to estimate the costs of constructing HDR electricity plants. These have relied on a variety of assumptions in regard to overall plant size, resource quality, drilling and fracturing costs, surface plant design, conversion efficiency, and the cost of money. Results have therefore been highly variable ranging from about $1,200 to more than $6,000 per installed kilowatt (Pierce 1993; Tester and Herzog 1990). Capital costs for HDR projects will obviously be highly site- and project-specific, but developing a better basis for making even general estimations of capital-cost factors is extremely important to the future development of an HDR industry.

The primary objective of HDR Program activities during Fiscal Year 1994 will be to support the move toward an industry-led HDR effort to construct and operate a facility to produce and market power from HDR resources in the competitive energy market. In the process of developing such a facility, the important capital cost issues relevant to HDR will be addressed and documented. Subsequently, operational costs, which should be fully covered by revenues generated from the sale of the energy produced, will be verified in a practical setting and for a meaningful period of time.

As a first step in developing an industry-led HDR initiative, the U. S. Department of Energy issued a Notice of Program Interest in late Fiscal Year 1993 soliciting private industry input with regard to a joint industry-government HDR effort. The replies that have been received in response to this Notice will form the basis for the development of the industry-led project. The program envisioned may involve further work at the Fenton Hill HDR site or the development of a second domestic HDR facility at a new location.

The Fenton Hill HDR pilot facility will be maintained on a standby basis during 1994. However, limited low-cost testing is being carried out with the objective of obtaining answers to questions which private industry may deem important to the success of the industry-led HDR development effort. Scientific and engineering support activities are being directed toward reviewing, analyzing, and documenting the results of recent flow-testing is underway. Again, the focus of the effort is on providing the important data needed for the impending industry-led HDR initiative.

Hopefully, the HDR work during 1994 will help set the stage for early commercialization of HDR by U. S. industry and lead to U. S. dominance of the extremely large clean-energy market that will develop for HDR in the coming decade. The end result should be a significant contribution to the growth and stability of the domestic geothermal energy industry, as well as energy-independence, trade, and job-creation benefits for the U.S. economy as a whole.

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